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Using QuickBird Sub-Metre Satellite Imagery for Implementation Monitoring and Effectiveness Evaluation in Forestry

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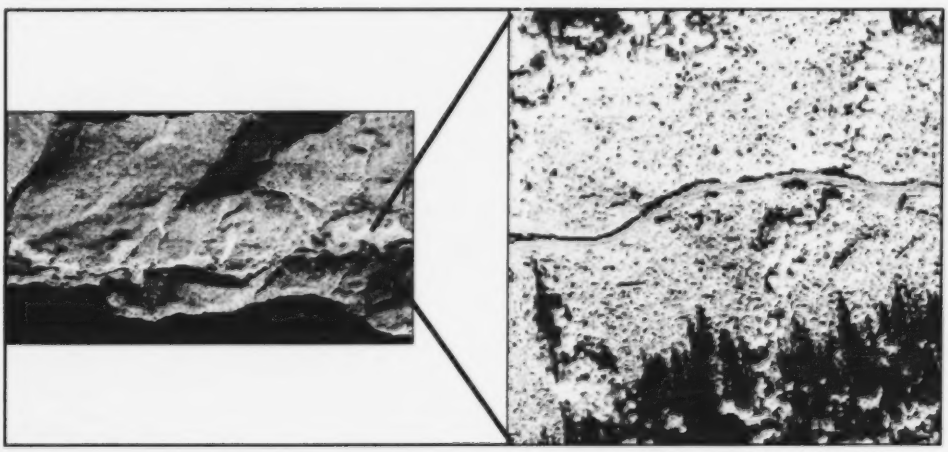

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Cover photo: QuickBird image of forested area, with close-up of harvested site.

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SUMMARY

Aerial photography, either black-and-white or color, and of variable scale, is the remote sensing technology with which most forest managers are familiar. Recently, forest managers have been adding other types of remote sensing to their toolboxes. For example, new commercial satellite platforms, such as DigitalGlobe's QuickBird satellite, provide imagery of far higher resolution than has been available in the past. QuickBird's sub-metre resolution, multispectral capability, high revisit frequency of 1–3.5 days, and its capability to cost-effectively acquire multispectral digital images over remote areas along the coast, are considered major advantages compared to the use of standard aerial photographs.

The use of high-resolution remote sensing technology for the purposes of managing sustainable forests was first investigated by the Vancouver Forest Region in 2001. In the follow-up project reported here, the primary objective was to determine the suitability of using the latest in very-high-resolution satellite imagery for forest management applications such as resource mapping, effectiveness evaluation, and implementation monitoring, and as a compliance and enforcement tool in variable terrain. QuickBird imagery was analyzed for the purpose of assessing resource features associated with forestry operations in two areas on the west coast of British Columbia. These features include conventionally harvested sites, roads, landslides, coarse woody debris, riparian areas, and road infrastructure activities.

KEYWORDS

Remote sensing, satellite imagery, QuickBird, applications, forest resource management, implementation monitoring, effectiveness monitoring, compliance and enforcement.

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1.0 INTRODUCTION

As part of the concept of sustainable development (Brundtland 1987), technological improvements were predicted to assist in measuring environmental performance, in conducting regular environmental assessments of compliance, and in providing appropriate information to the authorities in the case of non-compliance or illegal activity. Between 1993 and 1995, the Montreal Process Working Group (1998) formulated a set of criteria (essential factors of forest management against which forest sustainability can be assessed) and indicators (which provide a means of monitoring and measuring the effects of forest management action or inaction). The commercialization of high-resolution satellite imagery, such as that available from DigitalGlobe's QuickBird satellite, has given forest managers access to a new tool for monitoring and measuring some indicators of sustainable forests. Also, high-resolution satellite imagery provides the best-available infrastructure information about timber inventory over large areas.

The use of high-resolution remote sensing technology for the purposes of managing sustainable forests was first investigated by the Vancouver Forest Region in 2001 (Collins et. al 2001). In the follow-up project reported here, the goals were to determine the feasibility and effectiveness of using a very high-resolution optical spaceborne sensor and image processing technique to:

1. Identify and map forest resource features at two locations, one on the central mainland and one on the west coast of Vancouver Island, in British Columbia.

2. Monitor implementation and effectiveness of forest activities and forest resources. Effective monitoring is a significant issue for the regional Special Investigations Unit (SIU) of the Compliance and Enforcement (C&E) Section of the British Columbia Ministry of Forests, as well as for local forest district staff. Conventional monitoring relies heavily on ground-based methods, which are often difficult to execute in coastal British Columbia because many areas are remote and/or rugged.

3. Assist the South Island Forest District with determining and evaluating the status of roads, road deactivation work, and landslides in the Barkley Sound area in preparation of a transfer of the land tenure from the licensee to the government. The District wanted to determine the area occupied by roads and landslides, and determine the present condition of restoration treatments in order to identify areas needing a more rigorous evaluation or a more specific on-the-ground investigation.

As noted in Collins et al. (2001), from the perspective of operational forest management, the resource features of interest include, but are not necessarily limited to:

- landslides,
- roads,
- cutblocks (both clearcut and partial harvesting),
- vegetation types,
- stream channels and other aquatic and riparian features,
- wildlife habitats, and
- coarse woody debris.

In addition, other resource management activities, such as locating and estimating the amount of windthrow in an area and monitoring unauthorized harvesting, can be conducted using QuickBird imagery. Regarding the above resource features, remote sensing imagery has the capability to enable measurements and monitoring of change, both temporal and spatial, in distribution, condition, and extent. Measurements may include linear distances and bearings (e.g., roads and cutblock boundaries), area determination, and derived volume calculations (e.g., for timber harvesting), log counts and log-length estimates in booms on the water. Monitoring may include presence or absence of indicators (e.g., habitat condition), progress and results of resource management activities (e.g., road construction and deactivation), and compliance with conditions of resource management planning (e.g., harvesting in accordance with an approved plan). In addition, acquisition of remotely sensed data provides a baseline set of multispectral digital data for helping detect and analyze future changes.

2.0 METHODOLOGY

2.1 Study Areas

This assessment of the QuickBird data was conducted in the Vancouver Forest Region[1], at two locations (**Figure 1**):

Study Area 1: at Draney Inlet, on the central coast of the mainland.

Study Area 2: at Kennedy Lake in the Barkley Sound area, near Ucluelet on the west coast of Vancouver Island.

Study Area 1 is predominantly underlain by a heterogeneous granitoid gneiss which may include some undifferentiated dioritic complex mixed with metasediments and metavolcanics (Roddick 1996). Paleozoic to Mesozoic metamorphic rocks occur, with mid-Cretaceous granodioritic intrusive rocks to the extreme north and south. Study Area 2 is predominantly underlain by granitoid rocks of the Island Intrusions and Westcoast complex (Muller 1977).

The areas are situated within the transition between the very humid and very wet maritime Coastal Western Hem-

[1] The Vancouver Forest Region is one of several administrative areas in the province, as designated by the British Columbia Ministry of Forests. It is located in the southwestern portion of the province, and comprises eight Forest Districts.

lock biogeoclimatic zones (CWHvh and CWHvm). Predominant conifer species consist of western redcedar (*Thuja plicata*), western hemlock (*Tsuga heterophylla*), and amabalis fir (*Abies amabilis*). Many of the older wilderness roads and landslides are revegetated by red alder (*Alnus rubra*).

2.2 QuickBird Satellite

The satellite QuickBird-2 was launched on October 18, 2001. DigitalGlobe[2],[3] of Longmont, Colorado is the operator. It is a "next generation" satellite capable of collecting very high-resolution optical image data. QuickBird has a 0.61–0.72-m resolution panchromatic sensor and a 2.44–2.88-m resolution multispectral sensor, depending on the off-nadir viewing angle (**Table 1**). In addition it has a high revisit frequency of 1.0–3.5 days depending on latitude. The satellite orbits at an altitude of 450 km and the sensor has a coverage of 16.5–19 km in the across-track direction, which is 60–90% larger than any other commercial high-resolution sensor. QuickBird's Basic Image product is delivered as a rectangle (16.5 x 16.5 km) or as a strip (16.5 x up to 165 km) (Toutin and Cheng 2002). This is the highest spatial resolution satellite imagery commercially available.

Through a combination of different multispectral image channels, the QuickBird imagery provides a natural colour image and a false-colour infrared image that can be interpreted visually. The images are available in 0.61-m resolution black-and-white and 2.44-m resolution colour. The products are available in 11-bit black-and-white and 11-bit colour, which gives users 2048 shades of grey/colour (compared to only 256 shades of grey/colour for traditional 8-bit data). QuickBird products are sold by the square kilometer according to customer requirements. Prices for Basic Imagery (i.e., unprocessed imagery) are US$30/km^2 for either multispectral or panchromatic imagery, and US$30 + 50% for a multispectral/panchromatic image bundle. The minimum scene size for Basic Imagery is 272 km^2; however, for the purposes of this project an area of 64 km^2 was acquired for Study Area 1.

Figure 1. Locations of the two study areas.

The QuickBird imaging plane consists of six staggered panchromatic arrays and six staggered multispectral arrays. These arrays are known as DCA sensors. The layout of the DCA sensors used by the QuickBird satellite are shown in **Figure 2**.

2.3 Data Acquisition

To order the QuickBird imagery, corner coordinates of the area of interest were provided to Radarsat International, one of the Canadian data distributors. The initial search schedule was to acquire two images sometime during the period September to November 2002. The image for Study Area 1 was acquired by the QuickBird satellite on October 17, 2002 (**Table 2**). Due to excessive cloud cover in the area, the image for Study Area 2 was not acquired until January 17, 2003 (Table 2).

2.3.1 DCA Banding

Figure 3 shows an overview of the unprocessed image for Study Area 1. The image has noticeable vertical striping, called "DCA banding".[4] In this image we suspect that the DCAs could not compensate for the changes in brightness between the forested and the water areas.

Table 1. QuickBird specifications.

Product name	Spatial resolution at nadir (m)	Spectral bands (micrometres)	Dynamic range
QuickBird multispectral	2.44	Band 1: 0.45-0.52 (Blue) Band 2: 0.52-0.60 (Green) Band 3: 0.63-0.69 (Red) Band 4: 0.76-0.90 (Near-infrared)	11 Bit (2048 levels)
QuickBird panchromatic	0.61	Pan Band: 0.45-0.90	11 Bit (2048 levels)

[2] Formerly EarthWatch Incorporated.
[3] See http://www.digitalglobe.com.
[4] DCA banding occurs when one DCA array has a significantly different response from the next one—i.e., it may be darker or brighter than the adjacent one. The result is a "banding" effect. Each DCA has a gain control that reacts to ground features. If the areas on the ground have too much contrast/variation in land cover (e.g., a mixture of forested and urban areas), or too little contrast/variation in land cover (e.g., a forested area) plus poor lighting due to a bad sun angle, then the gain control of one DCA is different than the adjacent one.

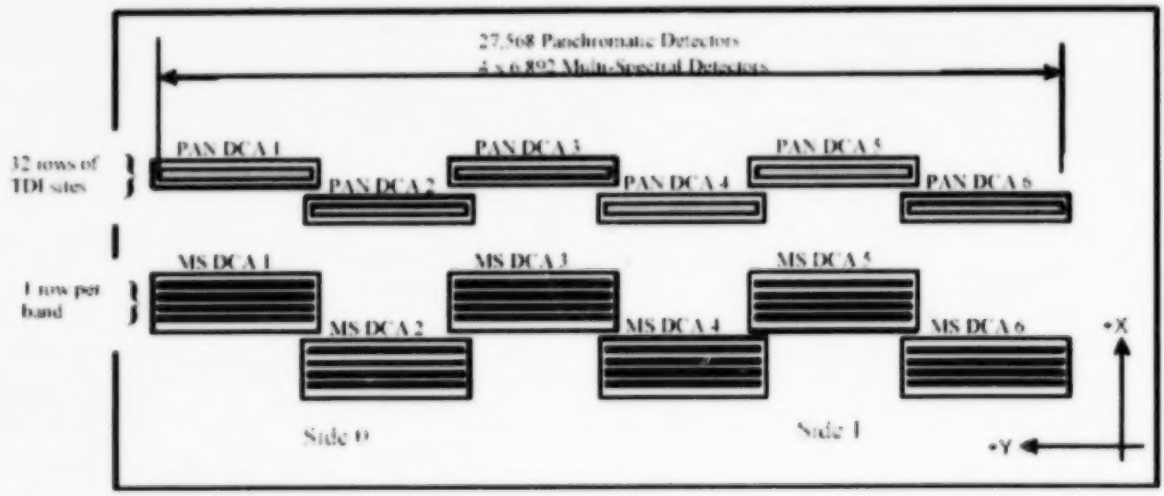


Figure 2. DCA sensor layout. (Source: http://ldcm.gsfc.nasa.gov)

Table 2. QuickBird order details.

Study Area 1	Order ID	10521
	Date of acquisition	October 17, 2002
	UL/LR coordinates	UL: 51.46361N, 127.55611W LR: 51.39028N, 127.43861W
	Pixel spacing	0.61 m panchromatic / 2.44 m multispectral
Study Area 2	Order ID	12704
	Date of acquisition	January 18, 2003
	UL/LR coordinates	UL: 49.08944N, 125.56583W LR: 48.92056N, 125.37278W
	Pixel spacing	0.61 m panchromatic / 2.44 m multispectral

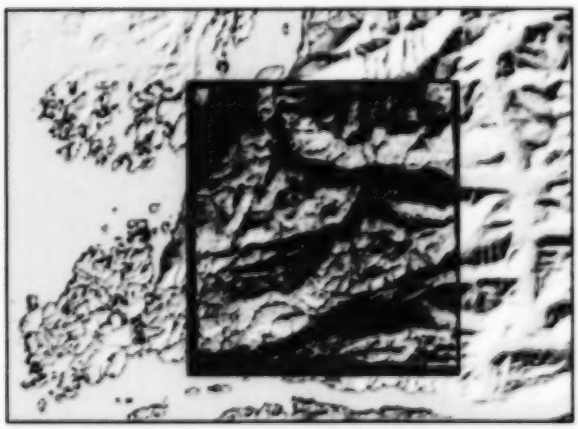


Figure 3. QuickBird coverage of Study Area 1, overlain on a hill-shaded digital elevation model of the area.

Figure 4 shows some of the DCA banding. In this particular case, the problem is compounded by the very low sun angle, due to imaging at high latitudes in mid winter. Shadows are quite apparent in the image, but details can be resolved within the shadowed areas because the image is collected with 11 bits of radiometric resolution (**Figure 5**).

2.4 Digital Image Processing Methodology

2.4.1 Orthorectification

The images were geocoded with the PCI® Orthoengine software.[5]

The first step in the image processing was to orthorectify the satellite images, and then produce composite images for interpretation. Both images were orthorectified to UTM

[5] See http://www.pci.on.ca.

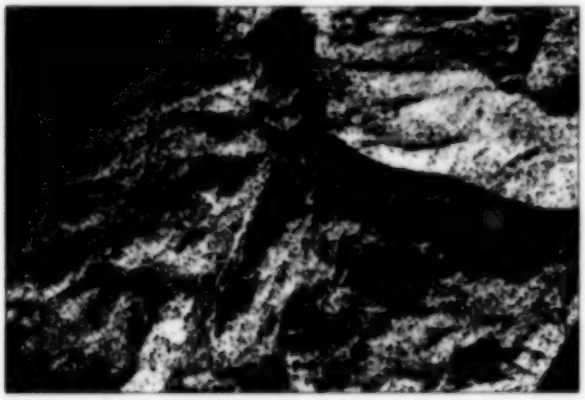


Figure 4. Effects of DCA banding. Note the western half of the scene has one tone of green while the eastern half of the scene has a completely different tone of green.

Figure 5. Details visible within shadowed areas of a QuickBird image.

Zone 10, NAD83 datum.Orthorectification of the QuickBird imagery followed these steps:

1. Ingesting the QuickBird panchromatic and multispectral images into PCI® Orthoengine. Each image needed to be split in half (with some overlap) due to a 1-GB limitation on the orthorectification software and limitations of the Windows operating system.

2. Ingesting a digital elevation model (DEM) that covers the area occupied by the QuickBird image into PCI® Orthoengine.

Ground control points (GCPs) that matched known features in the vector linework were identified in the QuickBird image. (Vector linework was loaded into MapInfo Professional GIS and viewed in conjunction with the PCI® Orthoengine session. The digital elevation model and some of the vector linework were provided from Terrain Resource Inventory Mapping–TRIM data.). An attempt was made to evenly distribute the locations of the ground control points across the imagery, so that the entire image could be rectified. The same ground control points that were applied to the panchromatic image were also applied to the multispectral image. For each image half, common control points were selected in the area of overlap so that there is no pixel shift between the two halves when they are later merged together. Appendix A shows the distribution of the ground control points and the root mean square (RMS) error for each ground control point.

The images were then orthocorrected using the digital elevation model. An output pixel size of 0.63 m was produced for the panchromatic imagery, and a pixel size of 2.5 m was produced for the multispectral imagery.

The images were then imported into ER Mapper® for producing composite images. Each orthorectified image half was mosaicked together to form a single panchromatic and multispectral image. Four QuickBird image combinations were produced:

(a) Combination of red, green, and blue channels with the panchromatic image.

(b) Combination of near-infrared, red, and green channels with the panchromatic image.

(c) Guided Principal Components image derived from blue, green, red, and near-infrared channels.

(d) Guided principal components image merged with panchromatic image.

Image combinations (a) and (b) were enhanced using the Balanced Contrast Enhancement Technique (BCET) transform, followed by contrast stretching. **Figures 6 and 7** show the individual bands as greyscale images and image combinations for Study Areas 1 and 2.

2.4.2 Principal Component Analysis

One of the digital processing techniques used for this project was guided Principal Component Analysis (PCA), which is a form of data merging and data compression. The PCA reduces the dimensionality or number of bands that the interpreter has to analyze to produce results. PCA is a statistical technique for compressing the spectral variance in multiple image bands into a subset of principal component (PC) bands, where each of the PC bands are uncorrelated with each other (**Figure 8**). This means that each PC band provides unique information not contained in the other PC bands. The first PC band (PC1) is basically the average of the input bands' values. The second PC band (PC2) contains the second-highest amount of scene variance not taken into account by the

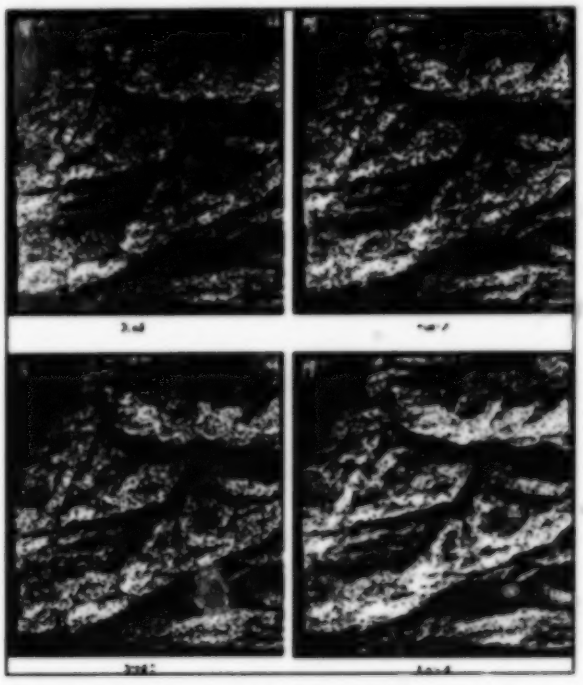


Figure 6 a. Panchromatic displays of blue, green, red, and near-infrared image bands, Study Area 1.

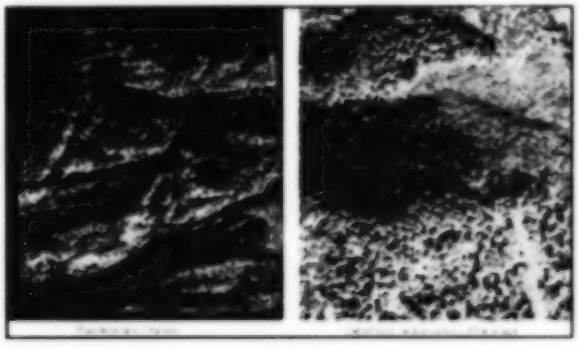


Figure 6 b. Display of panchromatic image band, Study Area 1.

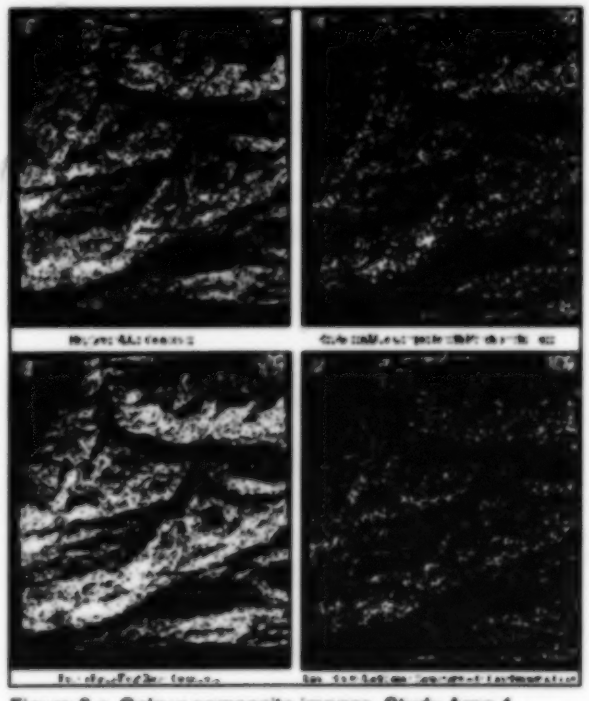


Figure 6 c. Colour composite images, Study Area 1.

first PC band. This process continues until the last PC band, which contains the least amount of unique scene variance information. Usually, the last PC band also contains scene noise. The concentration of scene variance in the first few PC bands reduces the number of image bands that need to be analyzed to produce results.

Because PCA considers the overall scene statistics, no single feature type is maximally separated. However, in general, a feature can become more separable. With guided PCA, a statistical sample area defined by the image analyst is used to transform the image channels. In this case, we digitized polygons of forested area, clearcut areas, and a combination of both. The statistics generated from these polygons should maximize the spectral variation between forest areas and clearcut areas, and should allow us to undertake more detailed analyses of these areas. **Figure 9** shows an example of how the overall scene scatter can differ from the scatter for different types of ground cover.

The factor loadings from guided PCA were reviewed, and bands were chosen based on having an inverse relationship between the visible and near-infrared channels. The bands that have very large positive and very large negative values were also checked because these could be viewed as pseudo ratios. These three classes of polygons were selected in order to determine whether small variations in the forest or clearcut features could be easily identified.

PCA channels (for display on an RGB computer screen) were chosen by reviewing the factor loadings of each PC channel (**Tables 3 and 4**). A channel was selected if it had a significantly high positive loading in one band and significantly high negative loading in another band, and the remaining bands had values near zero. PC channels of interest have factor loadings in bold.

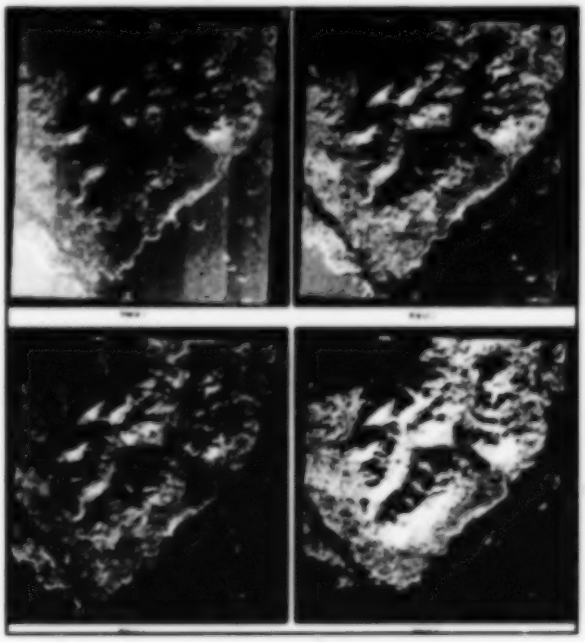


Figure 7 a. Panchromatic displays of blue, green, red, and near-infrared image bands, Study Area 2.

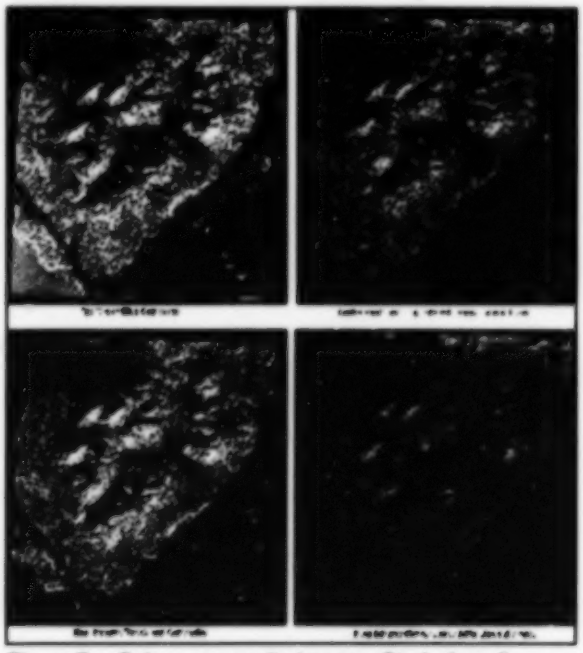


Figure 7 c. Colour composite images, Study Area 2.

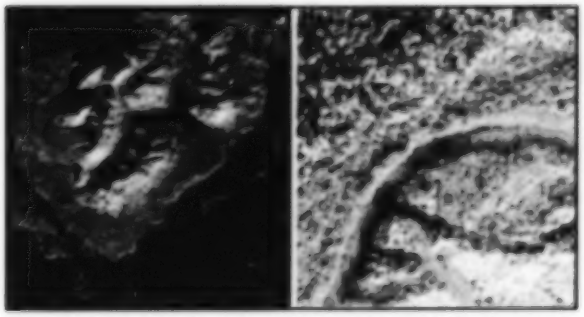


Figure 7 b. Display of panchromatic image band, Study Area 2.

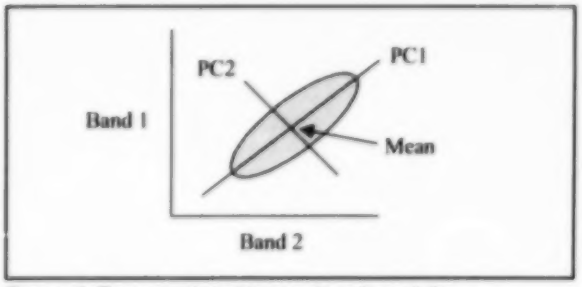


Figure 8. Two correlated image bands and the decorrelated PCA image axes.

For all PCA combinations of Study Area 1, PC1 and PC2 provide similar information. Primarily, PC1 represents the infrared band with some of the visible light band values. The near-infrared channel on its own should be as informative as PC1. PC2 is of some interest. It indicates a pseudo ratio between all three visible light band values and the near-infrared values. The near-infrared channel loadings are all close to zero so they may not be as useful as if they were much larger. In all PCA combinations, PC4 tends to show the noise in the image. Severe vertical banding in the images results from the PC4 image.

For Study Area 2, PC1 primarily represents near-infrared

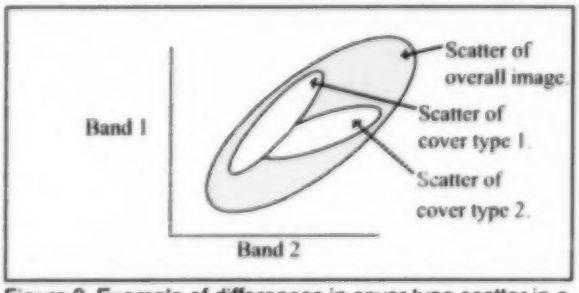


Figure 9. Example of differences in cover type scatter in a two-band image.

Table 3. PCA loadings, Study Area 1. Bold = PCA channels of interest.

	PC channel			
Spectral bands	**PC1**	**PC2**	**PC3**	**PC4**
Region: forest				
Cov. Eigenvectors				
Band 1: (Blue)	0.049206	-0.342449	-0.220417	**0.911989**
Band 2: (Green)	0.164741	-0.714124	**-0.544050**	**-0.408531**
Band 3: (Red)	0.124265	-0.573100	**0.809584**	-0.026235
Band 4: (Near-infrared)	0.977240	0.210503	-0.000133	0.026285
Region: clearcut				
Cov. Eigenvectors				
Band 1: (Blue)	0.001262	-0.377401	0.275478	**-0.884126**
Band 2: (Green)	0.064670	-0.672290	0.572113	**0.465329**
Band 3: (Red)	0.026798	-0.633927	-0.772347	0.029989
Band 4: (Near-infrared)	0.997546	0.061091	-0.016690	-0.029854
Region: forest and clearcut				
Cov. Eigenvectors				
Band 1: (Blue)	0.045822	-0.370252	0.184636	**-0.909243**
Band 2: (Green)	0.138600	-0.653195	**-0.734010**	0.123919
Band 3: (Red)	0.101224	-0.636955	**0.652975**	**0.397071**
Band 4: (Near-infrared)	0.984096	0.174753	0.027615	-0.015959

Table 4. PCA loadings, Study Area 2. Bold = PCA channels of interest.

	PC channel			
Spectral bands	**PC1**	**PC2**	**PC3**	**PC4**
Region: forest and clearcut				
Cov. Eigenvectors				
Band 1: (Blue)	0.07540	-0.30112	-0.46036	**-0.83169**
Band 2: (Green)	0.19239	-0.50384	**-0.63602**	**0.55191**
Band 3: (Red)	0.18281	-0.76339	**0.61760**	-0.04890
Band 4: (Near-infrared)	0.96119	0.26966	0.04596	-0.03593

light. PC2 is a ratio between visible light vs. near-infrared light, although the weighting for the near-infrared is not very large. PC3 shows a difference between green and red light, with a lesser representation by blue light. PC4 represents a ratio between blue and green light. PC4 tends to show the noise in the image. Severe vertical banding in the images results from the PC4 image. **Figures 10a and b** show colour composite images for Study Areas 1 and 2.

The PCA image analysis technique has proved useful for differentiating areas where forest cover has been removed, and this has significant application potential for compliance and enforcement activities.

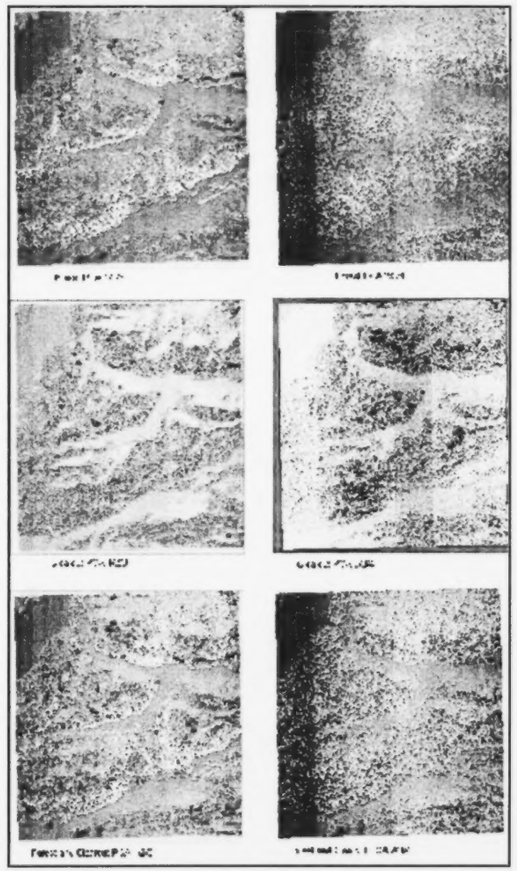


Figure 10 a. PCA colour composite images, Study Area 1.

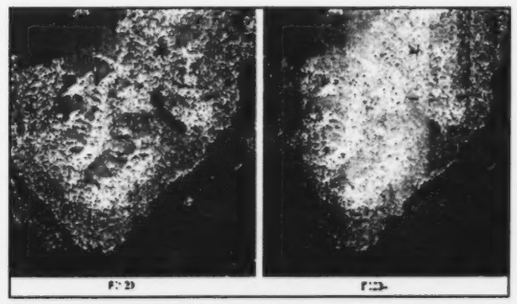


Figure 10 b. PCA colour composite image, Study Area 2.

3.0 FOREST RESOURCE MANAGEMENT APPLICATIONS

3.1 Monitoring and Evaluation

High-resolution satellite imagery has been used to classify and delineate different types of forest resource features, and for updating resource inventories in the Vancouver Forest Region (Collins et al. 2001). A major licensee on the mainland coast also uses it.[6] The sub-metre spatial resolution is so detailed that it allows single tree crowns to be differentiated. This level of detail makes the imagery very useful for monitoring a number of variables that can contribute to an overall implementation monitoring and effectiveness evaluation framework.

Some parameters that are readily discernible are:

- The amount of unmanaged forested land maintained in reserves or in lightly managed areas.
- The patch size and geographic distribution of those areas.
- Level of connectivity or fragmentation of a landscape.

Visual perspectives can be generated by using digital elevation models that provide a three-dimensional perspective of a landscape (**Figure 11**). A three-dimensional perspective view is produced by draping the satellite imagery over the elevation data from the TRIM topographic databases.

Also, Forest Development Plans can be updated by using high-resolution imagery. In addition, any anomalies

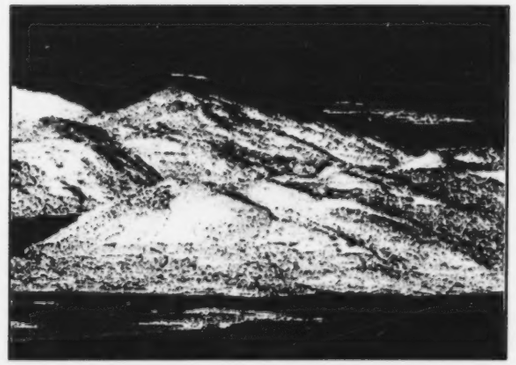


Figure 11. A 3D perspective view, Study Area 2.

[6] W. Warttig, Planning Forester, International Forest Products Ltd. (Interfor), Campbell River, British Columbia; personal communication, March 2003.

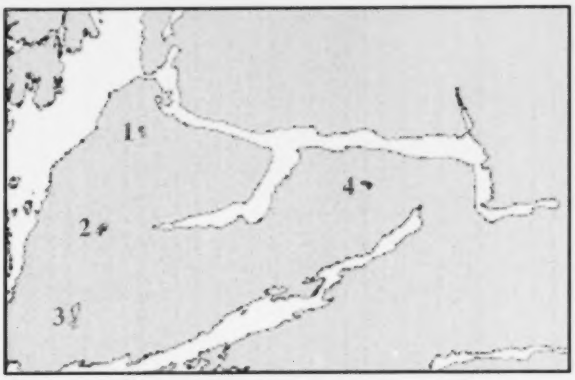
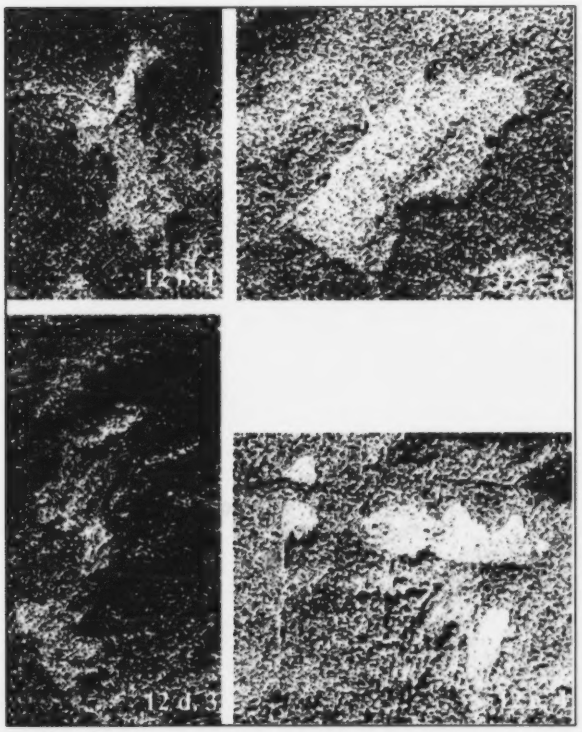


Figure 12 a. Location map for sample blocks. Block 1 = 0.08 km². Block 2 = 0.15 km². Block 3 = 0.30 km². Block 4 = 0.07 km².



Figures 12 b to e. Sample cutblocks.

or variances between the mapping and the imagery can be checked against the Silviculture Prescription, or can result in an on-site review to determine the status of the harvesting. In terms of updating timber inventories, harvested blocks can be digitized from the QuickBird imagery and the areas calculated. **Figure 12** shows the location of some harvested blocks in Study Area 1 and the area of each block. These were compared to the Forest Development Plans.

The imagery can also be used in implementation monitoring, for routine effectiveness evaluation of harvesting activities, and for monitoring spatial distribution of resource features that are being manipulated operationally to attain management objectives and may be useful in developing assumptions for Timber Supply Reviews (e.g., monitoring Wildlife Tree Patches as an indicator of the amount and distribution of forest stands, or monitoring the provision and distribution of coarse woody debris over the landscape). In **Figures 13 a, b, and c**, and in **Figures 14 a and b**, the Forest Development Plan for a series of cutblocks in one study area has been plotted, and the high-resolution imagery was used to compare the planned activities with the actual ground work. This reveals some variance in one Wildlife Tree Patch in one block (Figures 13 a and b. In a more-detailed review there appears to have been a landslide which has removed the upper portion of the Wildlife Tree Patch (Figure 13 c). In Figure 14, variances between the Forest Development Plan and the actual harvest pattern are visible. A case such as this would be designated for follow-up by the appropriate personnel.

3.1.1 Coarse Woody Debris

As noted in Collins et al. (2001) high-resolution imagery can be used as a component of a multi-phase approach for determining the extent of coarse woody debris on cutblocks (**Figure 15**). The number of large pieces of a specific length can be measured from the imagery (**Figure 16, Table 5**). This type of analysis can allow the amount of downed wood to be compared in terms of pre-harvest and post-harvest, and relative to different silviculture systems and forms of retention. This work could then be followed by on-the-ground assessment for classification purposes. (Additional analysis and ground truthing would be required to determine whether dead standing wood could be detected at the single-tree level.)

The QuickBird imagery could be useful for preliminary waste assessments and helping to determine which harvested areas need follow-up ground surveys to determine what is waste (as per cutting permit specifications) and what is legitimate coarse woody debris. In addition, the analysis can contribute to the operational decisions in an adaptive management planning cycle such that any shortfalls or excesses can be recognized and incorporated into operational plans.

While variable amounts and distributions of coarse woody debris are desirable across the landscape, some piling and burning of coarse woody debris along roadsides is also conducted. These features can be identified on the high-resolution imagery (**Figure 17**).

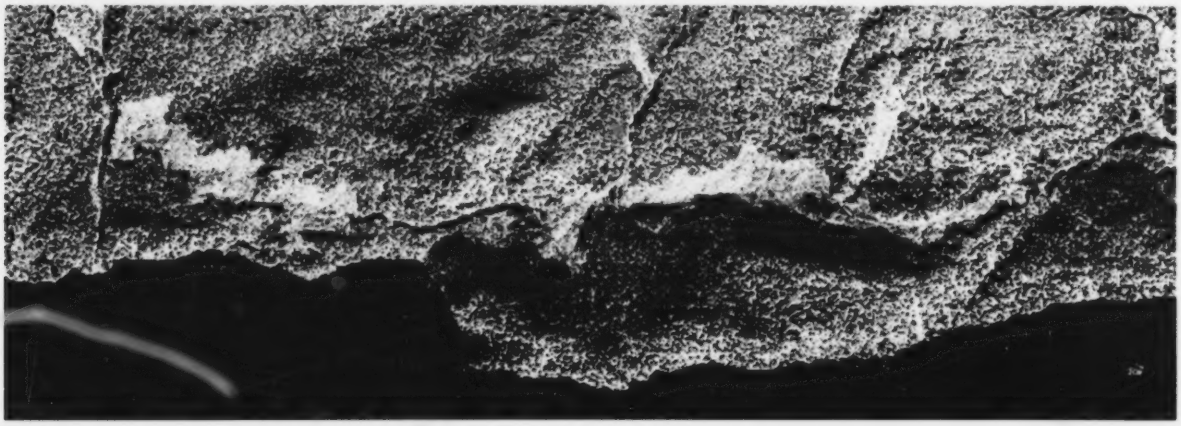


Figure 13 a. Overview of cutblock, Study Area 1.

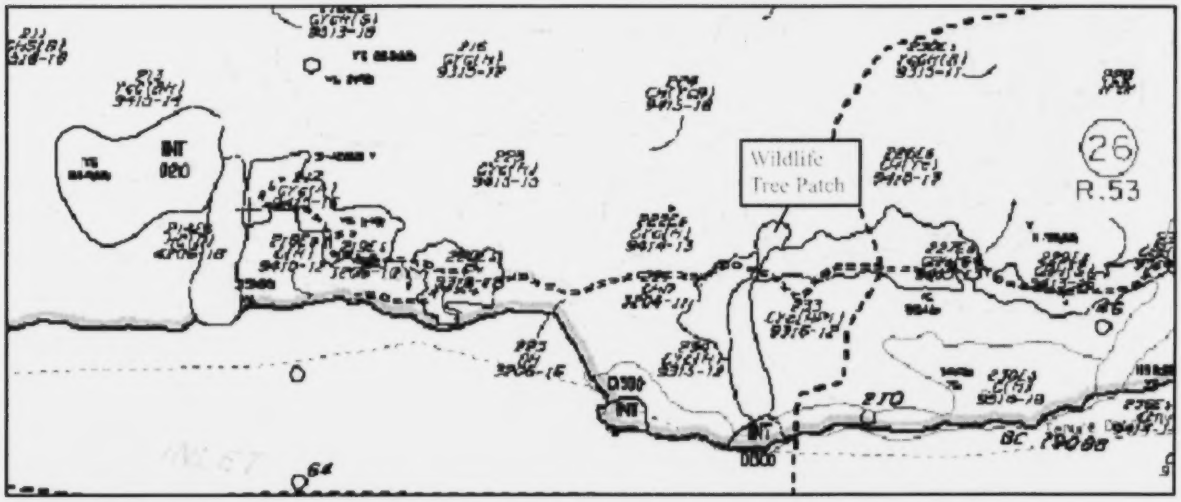


Figure 13 b. Forest Development Plan for area of interest.

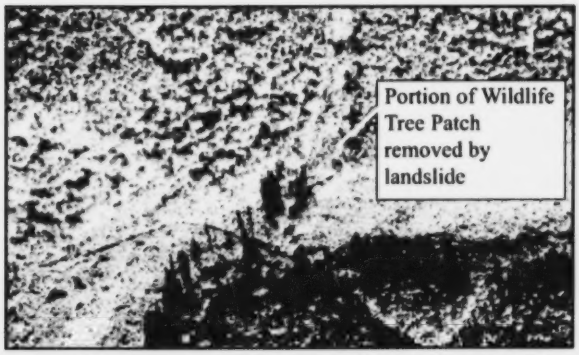


Figure 13 c. High-resolution view of Wildlife Tree Patch in cutblock.

3.1.2 Road Density and Distribution

Road density, width, and area occupied by road-related infrastructure can be calculated from high-resolution satellite imagery. Total road density by road type (active, deactivated, overgrown) can be calculated.

The road network in the Barkley Sound area was digitized, and road width and turn-out areas were calculated from the imagery (**Figure 18, Table 6**). Road widths varied from 4 to 20 m, and averaged 9 m. Roads occupied 3.25 km^2, or 2.11%, of the total area.

[7] Doug Erickson, Engineering Officer, BC Ministry of Forests, South Island Forest District; personal communication, January 2003.

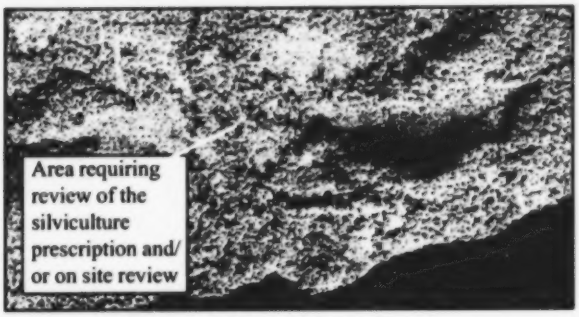


Figure 14 a. Helicopter blocks, Study Area 1.

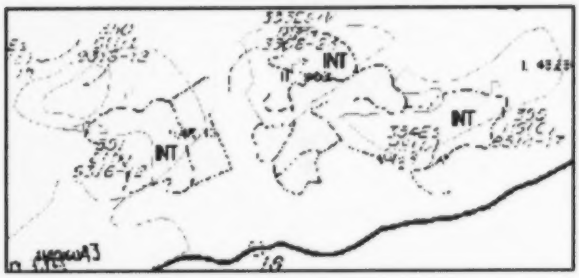


Figure 14 b. Forest Development Plan, helicopter blocks, Study Area 1.

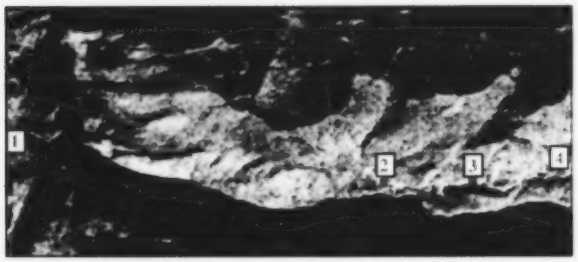


Figure 15. Four sample areas within harvested blocks, for coarse woody debris analysis.

In a pilot study of road widths in other parts of the South Island Forest District, District staff found that the width of mainlines averaged 17 m, spur roads averaged 10 m, and in-block roads averaged 6 m.[7] The District uses an average road width of 10 m for timber supply analysis. **Figure 19** shows individual cross-ditches which have been installed across the road width and waste burn piles along the road margins. Individual logs can be differentiated on some of the waste piles.

The density of stream crossings can also be discerned on the imagery; this knowledge can be a significant factor in planning and monitoring of road infrastructure. The

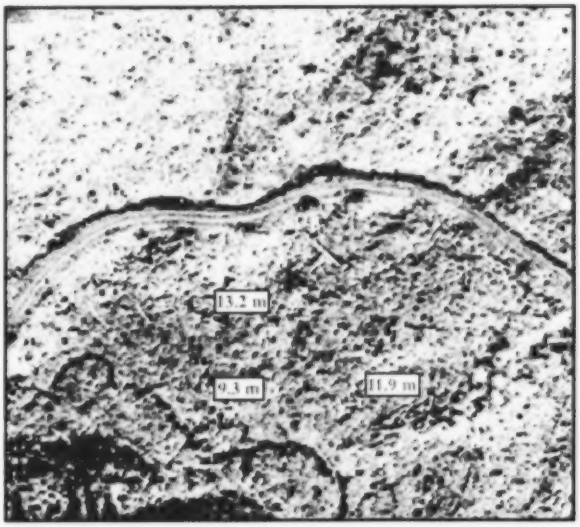


Figure 16. Coarse woody debris: lengths of selected logs.

Table 5. Amount of woody debris within four sample areas.

Polygon label	Size of sample area (ha)	Total length of CWD (m)
1	1.00	283.88
2	1.00	224.91
3	1.00	428.23
4	1.00	246.20

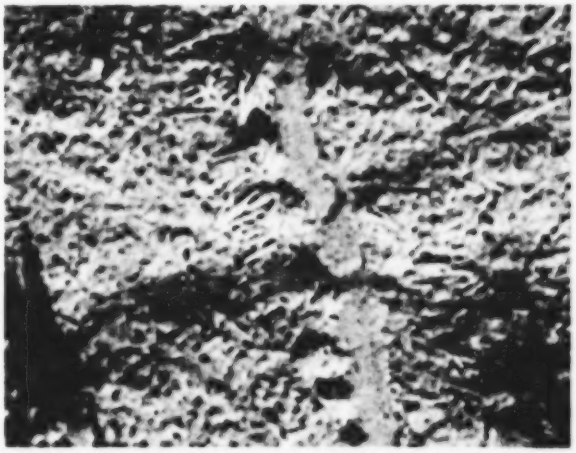


Figure 17. Waste, piled for burning along a road margin.

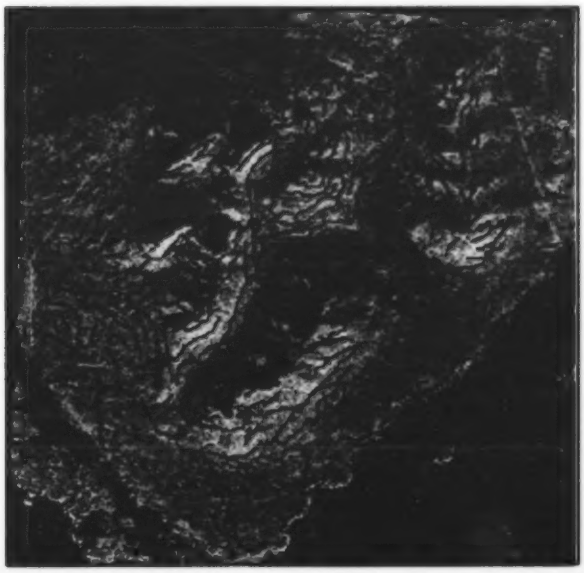


Figure 18 a. Digitized road infrastructure, Study Area 2.

Figure 18 b. Digitized road infrastructure, Study Area 2. Note, resolution is sufficient to determine roads in shadowed areas of the imagery.

status of the Riparian Zones and the presence or absence of Riparian Reserve Zones can be visually assessed on the imagery (**Figure 20**).

The extent and success of past rehabilitation efforts, and opportunities for future rehabilitation activities, may be determined from the QuickBird imagery. In **Figure 21**,

Table 6. Road density and distribution, Study Area 2.

Measured road widths (m)	Road segments [a] (no.)	Total length of roads (km)	Total area occupied by roads (km^2)	Avg. road width (m)
4-9	405	191.27		
>9-12	188	120.61		
>12-20	43	32.4		
Data not available	56	28.89		
Total	692	373.17	3.25	9

[a] A road segment is defined as a section of road between two road intersections, or between an intersection and the end of a road (e.g., turn-around area, landing).

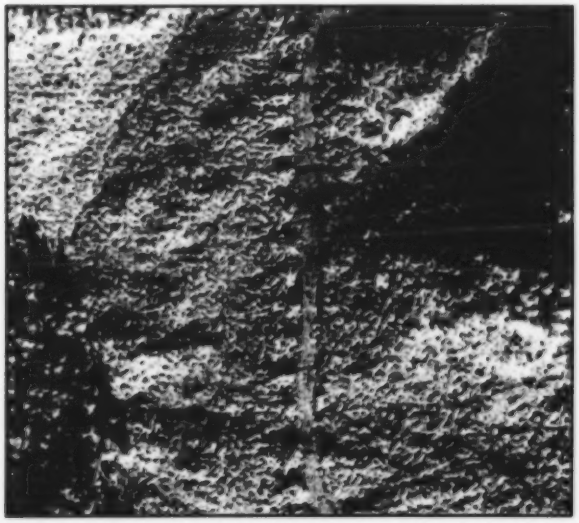


Figure 19. Cross ditches installed across a road. Note waste, piled for burning along road edge.

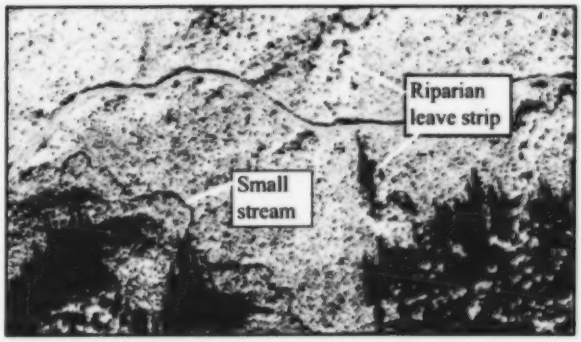


Figure 20. Monitoring of riparian leave strips.

Figure 21. Near-infrared and panchromatic fused image showing deactivated road with some coarse woody debris scattered over recontoured surface.

the near-infrared image highlights three distinct levels of vegetation: (a) forested, (b) new regeneration, and (c) thin ground cover. Revegetation does not appear to be vigorous across the entire road width of the recontoured, deactivated road. Ground truthing conducted in other areas suggests that some encroachment by alder has probably occurred, but it has not been detected on the near-infrared image due to lack of leaf cover. From an effectiveness evaluation perspective it appears that many deactivated roads could benefit from a follow-up fertilization treatment to enhance the growth of any vegetation cover and confer seedlings that have been planted.

3.1.3 Landslides

Landslide areas can also be calculated from the QuickBird imagery. The types of disturbance, origins or initiation points of disturbance, area of disturbance and runout zones, connectivity to streams, and the degree to which the disturbed area has been revegetated, are identifiable. In addition, the spatial distribution of the sediment sources is readily apparent. The high resolution also facilitates estimation of the amount of timber that may be available for salvage from the deposition zones of some slides.

One particularly useful technique for visual interpretation of the imagery is to use PCA image processing techniques (see section 2.4.2) to highlight areas where the forest cover may have been removed. For example, in this study, the PCA colour composite showed differences between forested areas, harvested areas, and bare ground in terms of such features as landslide areas. **Figure 22** shows a large, open-slope landslide that has removed a large amount of forest cover in the initiation and transport zones. The deposition zone contains a significant amount of timber, some of which appears to have been deposited along the ocean margin. The forest and the forest+clearcut PCA images show colour differences between the transport and deposition zones of the largest landslide. **Figure 23** provides another example of how subtle differences in a slide area are visible in a PCA image, but not visible in a false colour infrared image.

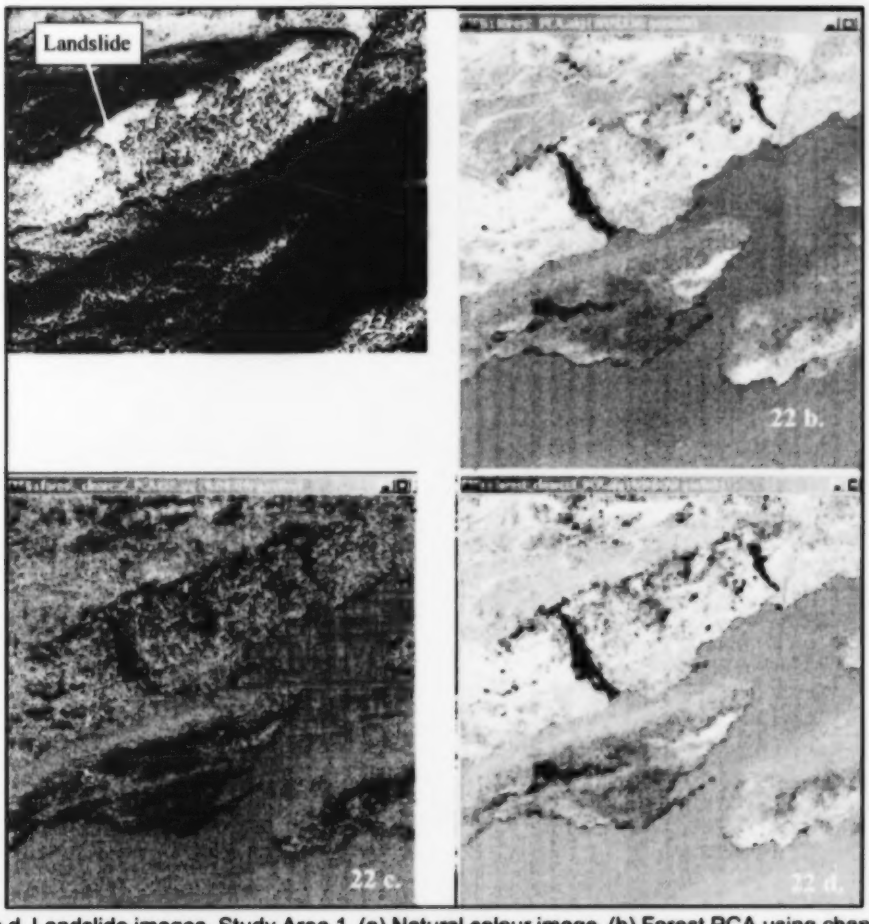
One of the significant differences between digital aerial photographs and satellite imagery is that the latter's multispectral sensor provides the capability of viewing spectral information in the visible and near-infrared portions of the electromagnetic spectrum, therefore differences in reflectance can be used to map areas of different surface cover and provide general indications of condition. In **Figure 24** older landslides that have been revegetated can be differentiated. This capability can be used for monitoring purposes and could be extended to in-block applications such as assessment of achievement of green-up and free growing requirements.

3.1.4 Compliance and Enforcement

QuickBird can be used as an effective compliance and enforcement tool to observe operations in areas that are difficult to access, such as remote coastal sites. Salvage and log boom operations can be readily identified. **Figures 25a and 25b** show various marine log salvage operations in Study Area 1.

The resolution of the imagery allows length of piece size and piece count to be determined prior to on-ground inspection.

As noted earlier, one particularly useful technique was to use PCA image processing techniques to highlight areas that may represent areas where the forest cover has been removed (**Figures 26 and 27**). The PCA colour composite showed differences between forested, harvested, and landslide areas in the image. This process has proved to be useful in highlighting areas that warrant on-site inspection to determine if illegal harvesting activities or blowdown have occurred. The PCA images highlighted individual canopy gaps that may represent low-volume tree removal, as well as patches along the coast line that, upon ground truthing, appear to represent sites where trees have been illegally removed. Other zones with partial tree removal were also delineated in this fashion and targeted for further investigation on the ground. To help



Figures 22 a to d. Landslide images, Study Area 1. (a) Natural colour image. (b) Forest PCA using channels 1/2/3. (c) Forest+clearcut PCA channels 2/3/4. (d) Forest + clearcut PCA channels 1/2/3.

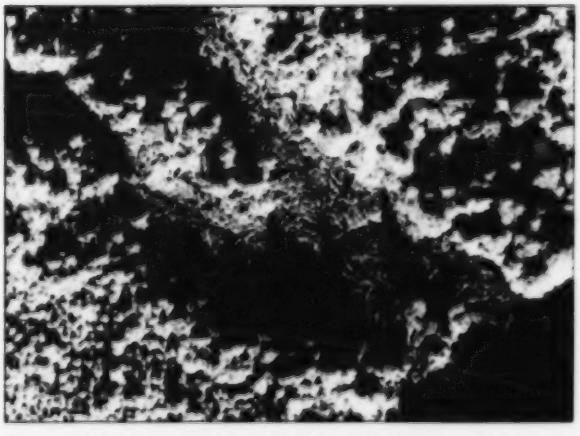


Figure 22 e. Salvageable timber in landslide deposition zone.

prioritize and maximize efficiency of on-ground inspections, natural colour and PCA images of Study Area 1 were visually reviewed in conjunction with the staff of the Special Investigations Unit. Specific targets that warranted on-site inspection were identified and hardcopy images were provided to the Special Investigations Unit for use in the field. This type of information will continue to be of assistance in the prioritization of compliance and enforcement activities in remote areas along the coast.

4.0 CONCLUSIONS

The use of high-resolution remote sensing technology for the purposes of managing sustainable forests was first investigated by the Vancouver Forest Region in 2001 (Collins et al. 2001). In the follow-up project reported here, the primary objective was to determine the suit-

Figure 23 a. False colour infrared image of a landslide, Study Area 2.

Figure 23 b. PCA 1/2/3 image of same landslide, Study Area 2.

ability of using the latest in very-high-resolution satellite imagery for forest management applications such as resource mapping, effectiveness evaluation, and implementation monitoring, and as a compliance and enforcement tool in variable and remote terrain. QuickBird imagery was analyzed for the purpose of assessing resource features associated with forestry operations in two areas on the west coast of British Columbia.

Figure 24 a. Natural colour image of recent and older landslides.

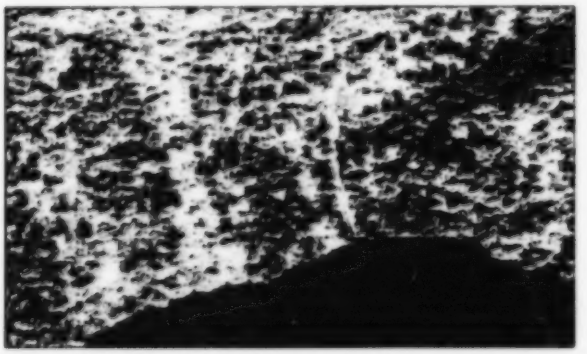


Figure 24 b. Near-infrared image showing recent and older landslides.

Two Quickbird images of two different sites were acquired, one in October 2002 and one in January 2003. That the imagery was acquired in the winter was a limiting factor because the low angle of the sun produced significant shadow affects. However, even in the shadowed areas, the 11-bit data did provide adequate information to delineate road networks. The January image also contained significant banding which can be avoided if the imagery is acquired in the summer or early fall months. This banding also limits the extent to which quantitative image analysis treatments can be applied to the imagery.

From a forest stewardship perspective it is likely that the use of high-resolution satellite imagery will provide valuable long-term data for monitoring and detecting change across the landscape. Over time this data will form a valuable source of information for reporting on the state of forests.

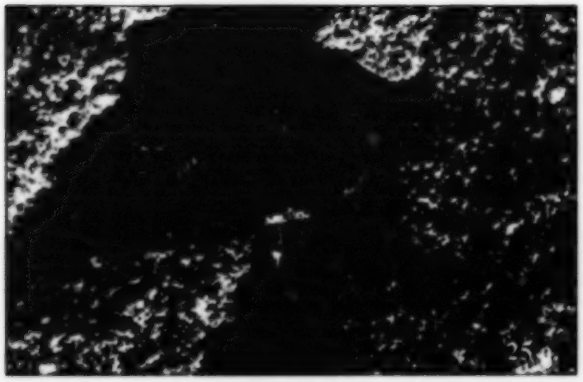
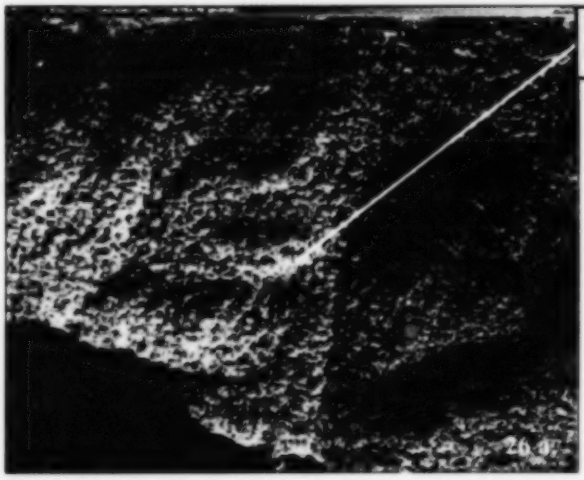


Figure 25 a and Figure 25 b. Various marine log salvage operations.



PCA technique to highlight areas of interest such as canopy gaps for investigation of tree removal or blowdown.
Original polygon area classified in harvested area.

Figure 26 a and Figure 26 b. Identifying forest cover gaps: PCA image.

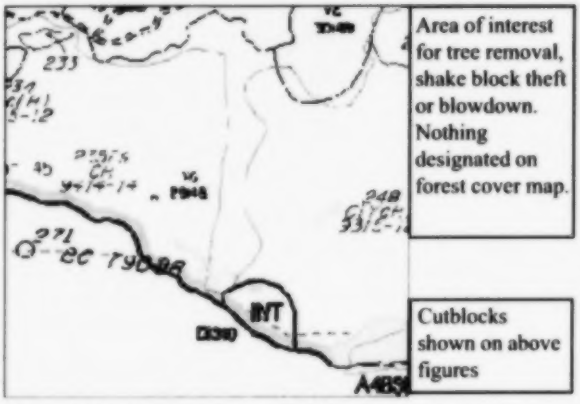

Area of interest for tree removal, shake block theft or blowdown. Nothing designated on forest cover map.
Cutblocks shown on above figures

Figure 26 c. Forest cover map of areas of interest.

5.0 REFERENCES

Brundtland, G.H. 1987. *Our Common Future: The World Commission on Environment and Development.* Oxford University Press, NY.

Collins, D.; K. Kliparchuk; M. Connor; and W. Warttig. 2001. *Preliminary Assessment of the Application of Ikonos Satellite Imagery and its Fusion with Radarsat-1 Data for Forest Resource Management.* Research Section, Vancouver Forest Region, BC Ministry of Forests, Nanaimo. Technical Report TR-014, Tools and Applications.

The Montreal Process Working Group. 1998. *The 'Santiago Declaration': Criteria and Indicators for the Conservation and Sustainable Management of Temperate and Boreal Forests: The Montreal Process Meetings and Reports.* See http://www.mpci.org/criteria_e.html.

Figure 27 a. Site of suspected tree theft, along coastline.

Muller, J.E. 1977. *Geology of Vancouver Island, April 21–24: Geological Association of Canada, Mineralogical Association of Canada, Joint Annual Meeting, 1977, Vancouver, B.C./Guidebook.* Field Trip Guidebook No. 7.

Roddick, J.A. 1996. Geology, Rivers Inlet (92M) – Queens Sound, BC (102P). Geological Survey of Canada, Ottawa, Ontario. Open File 3278. Map compilation plus two volumes of text and four diskettes.

Toutin, T. and Cheng, P. 2002. "QuickBird—A Milestone for High-Resolution Mapping" pp. 14–18 in *Earth Observation Magazine.* Vol. 11, No. 4, April 2002. Professional Surveyors Publishing Company, Inc., Maryland. See preprint at http://www.ccrs.nrcan.gc.ca/ccrs/rd/sci_pub/bibpdf/13212.pdf.

Figure 27 b. PCA image showing site of suspected tree theft, along coastline.

APPENDIX A: RMS ERROR REPORTS FOR STUDY AREA 1 [1]

Residual Units: Image Pixels
Residual Info for 1 Images
GCPs: 19 X RMS 5.19 Y RMS 1.25
Check Points: 1 X RMS 22.70 Y RMS 0.76
Listing: All points All Images

Point ID	Res	Res X	Res Y	Type	Photo X	Photo Y	Comp X	Comp Y
G0023	22.71	-22.7	0.76	Check	441.6	14257.4	418.9	14258.1
G0008	9.85	-9.64	-2.04	GCP	27443.4	12277.1	27433.7	12275.1
G0012	8.97	8.71	-2.15	GCP	16328.6	19308.4	16337.3	19306.2
G0013	7.46	-6.85	2.96	GCP	25337.9	18193.1	25331	18196.1
G0021	7.14	7.13	0.43	GCP	14289.1	15507.9	14296.3	15508.3
G0010	6.41	-6.41	0.11	GCP	1518.3	17970.3	1511.8	17970.4
G0005	6.23	-6.2	-0.63	GCP	2454.4	11398.6	2448.2	11397.9
G0009	5.47	5.27	-1.48	GCP	18544.1	11479.4	18549.4	11477.9
G0015	5.45	5.39	-0.82	GCP	9758.6	26844.4	9764	26843.6
G0002	5.07	5.07	-0.08	GCP	6597.8	1309.8	6602.8	1309.7
G0001	4.18	-4.18	0.05	GCP	1358.2	447.7	1354	447.7
G0017	3.76	-3.65	0.9	GCP	24851.1	25726.4	24847.4	25727.3
G0003	3.17	2.26	2.22	GCP	15166.4	2244.1	15168.6	2246.3
G0014	2.66	-2.66	0.13	GCP	839.1	26673.6	836.5	26673.8
G0016	2.09	2.09	-0.03	GCP	19905.9	28222.8	19908	28222.8
G0022	2.08	2.08	-0.07	GCP	23158.6	14899.6	23160.7	14899.6
G0020	1.88	1.76	0.66	GCP	5132.4	15513.9	5134.1	15514.5
G0011	1.16	-0.99	0.61	GCP	9722.8	18161.3	9721.8	18161.9
G0004	0.99	0.63	-0.77	GCP	26664.1	3344.4	26664.8	3343.6
G0006	0.91	0.82	-0.39	GCP	11227.8	11721.8	11228.6	11721.4

[1] Note, the GCP Residual Error Report for Study Area 2 is not shown here because the computer containing the GCPs was stolen.

Residual Units: Ground Units
Residual Info for 1 Images
GCPs: 19 X RMS 3.25 Y RMS 0.80
Check Points: 1 X RMS 14.10 Y RMS 0.83
Tie Points: 0 X RMS Y RMS
Listing: All points All Images

Point ID	Res	Res X	Res Y	Type	Ground X	Ground Y	Ground Z	Comp X	Comp Y
Point	14.121	14.096	0.829	Check	595958.906	5696029.219	604	595973	5696030.05
Point	6.207	6.111	-1.088	GCP	612797.969	5697685.781	629	612804.08	5697684.69
Point	5.597	-5.403	-1.461	GCP	605996.719	5693174.531	65	605991.32	5693173.07
Point	4.731	4.302	1.969	GCP	611627.031	5694012.031	0	611631.33	5694014
Point	4.445	-4.442	0.164	GCP	604673.906	5695501.094	144	604669.46	5695501.26
Point	3.991	3.988	0.169	GCP	596725.156	5693769.219	134	596729.14	5693769.39
Point	3.877	3.866	-0.295	GCP	597231.094	5697866.406	254	597234.96	5697866.11
Point	3.415	-3.267	-0.994	GCP	607311.094	5698086.406	15	607307.83	5698085.41
Point	3.387	-3.337	-0.581	GCP	601969.453	5688383.359	10	601966.12	5688382.78
Point	3.163	-3.16	-0.131	GCP	599749.531	5704229.531	0	599746.37	5704229.4
Point	2.604	2.602	0.094	GCP	596469.531	5704683.594	3	596472.13	5704683.69
Point	2.435	2.345	0.655	GCP	611330.781	5689281.719	467	611333.13	5689282.37
Point	1.967	-1.423	1.358	GCP	605010.781	5703725.781	766	605009.36	5703727.14
Point	1.659	1.654	0.121	GCP	596402.656	5688350.156	7	596404.31	5688350.28
Point	1.263	-1.262	-0.028	GCP	608312.656	5687677.344	97	608311.39	5687677.32
Point	1.255	-1.254	-0.042	GCP	610112.656	5695966.094	881	610111.4	5695966.05
Point	1.162	-1.097	0.385	GCP	598964.531	5695358.906	72	598963.43	5695359.29
Point	0.745	0.624	0.407	GCP	601794.844	5693748.281	549	601795.47	5693748.69
Point	0.573	-0.347	-0.456	GCP	612154.219	5703196.094	1152	612153.87	5703195.64
Point	0.556	-0.499	-0.245	GCP	602670.156	5697780.156	563	602669.66	5697779.91